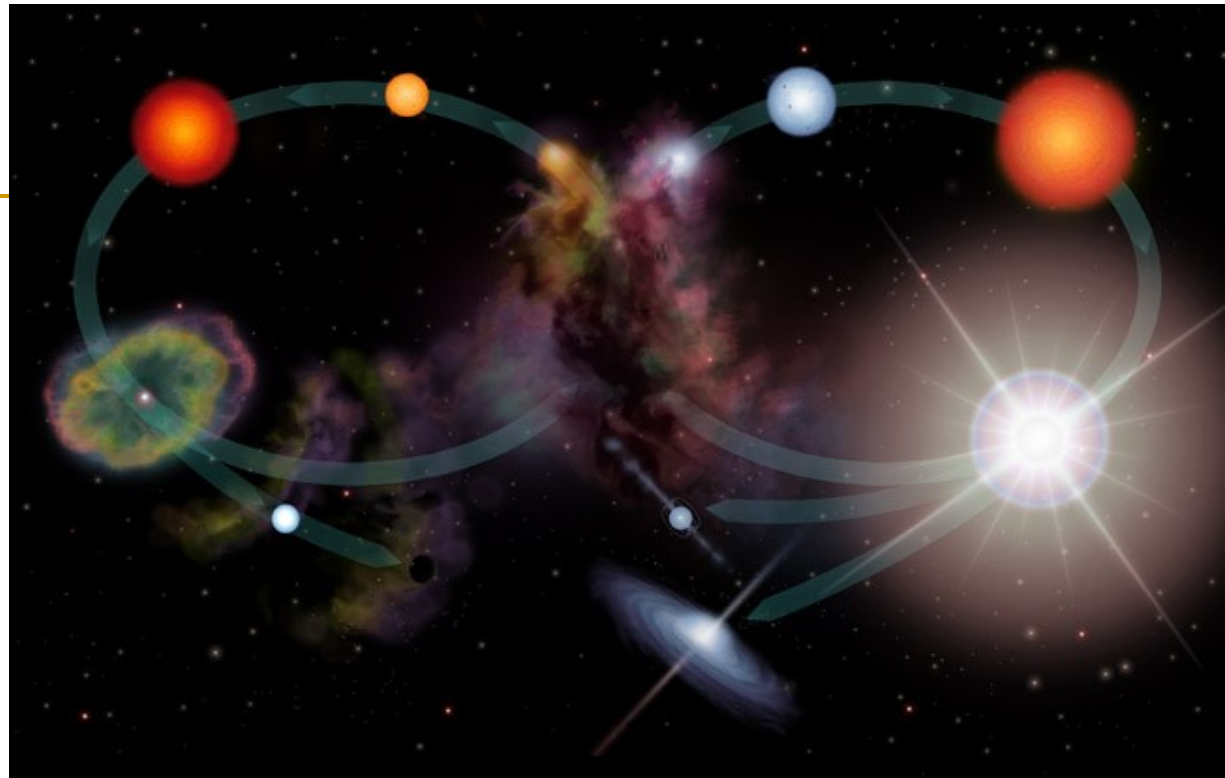
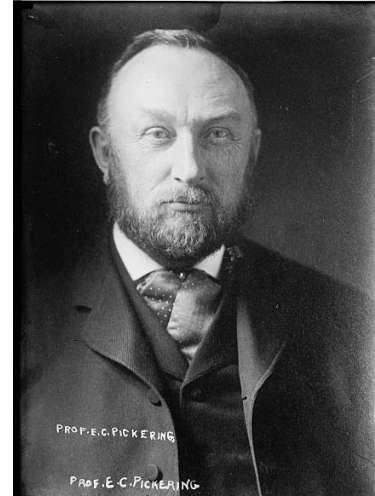


Lives of Stars



Stellar spectral classes

- Edward Pickering (1846 – 1919) was a Director of Harvard Observatory until his death.
- He recruited women to work as “human computers” (Annie Cannon, Williamina Fleming, Henrietta Levitt)
- In 1912 Annie Cannon (1863 – 1941) discovered that most stars fall into several classes: O, B, A, F, G, K, M, based on their color.

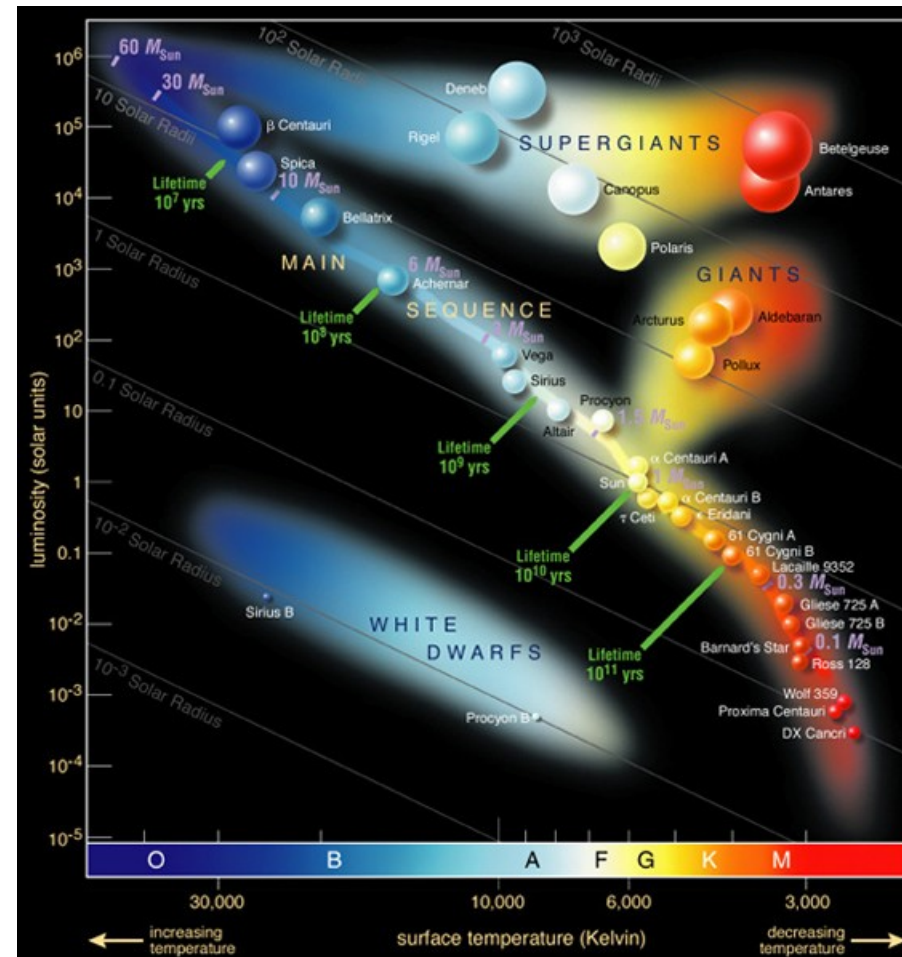


Hertzsprung – Russel diagram

- Two most easily observable properties of stars are their **color** (= temperature) and **magnitude** (=luminosity).
- In 1910 Ejnar Hertzsprung (1873 – 1967) and Henry Russel (1877 – 1957) made the first stellar **color – magnitude diagram** (or **CMD**).
- To their surprise, they found that stars do **not** have all possible luminosities and colors, but fall along several clear tracks.
- The main track is called the **main sequence**, the rest are called **branches**.

H-R diagram

- Main sequence (***MS***) includes more than 90% of all stars.
- Two main branches are the ***Red Giant Branch (RGB)*** and the ***Horizontal or Supergiant Branch (HB)***.



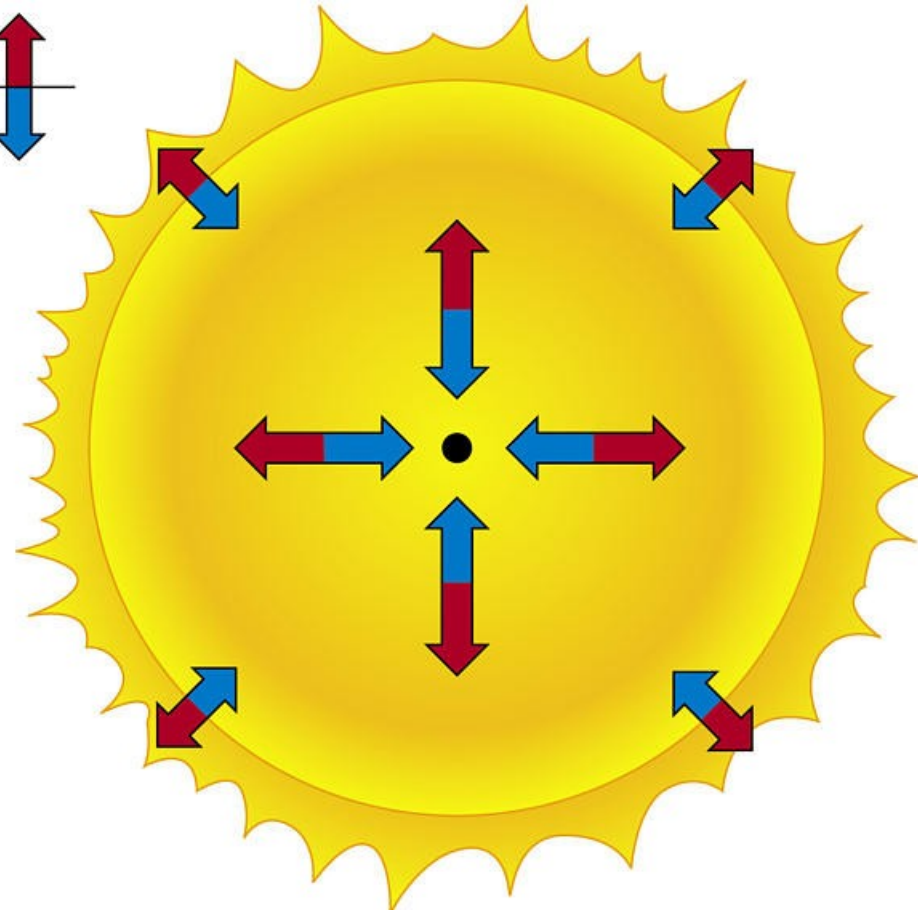
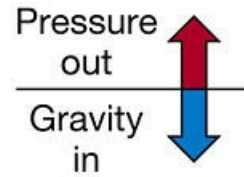
Why are stars round?

- **A:** because a sphere is a perfect shape.
 - **B:** because the pressure balances gravity in every place inside a star.
 - **C:** because gravity pulls down equally in all directions.
 - **D:** because they rotate very fast.
 - **E:** because they are made out of gas.
-

Maintaining the equilibrium

- Inside stars pressure balances gravity everywhere, stars are said to be in ***hydrostatic equilibrium***.

$$\frac{dP}{dr} = -\rho \frac{GM}{r^2}$$



Arthur Eddington (1882 – 1944)

- Produced the first observational test of General Relativity by observing light deflection near the Sun during a full solar eclipse.
- In his 1920 article “The Internal Constitution of the Stars”, he founded the modern theory of stellar structure and evolution.



Eddington's 3 principles

- Hydrostatic equilibrium (stars live very long, so they ought to be in the equilibrium).
- Energy transport: radiative diffusion and/or convection.
- Energy production: nuclear reactions via pp chain.
- Nuclear physics was in its infancy in 1920 (neutron was only discovered in 1932 by James Chadwick), so Eddington could not figure out how nuclear reactions proceeded in stars.

Hans Bethe (1906 – 2005)

- German immigrant to the US.
- In 1939 finally figured out how the CNO cycle works in massive stars.
- In 1931 made fun of Eddington for his devotion to numerology.
- Published his last research paper when he was 91 years old.



Stellar ecology

- If stars are in the hydrostatic equilibrium, have the same chemical composition, and just burn hydrogen at their cores, then the only quantity that matters is the stellar ***mass***.
- All other properties of stars should depend on only their masses.
- On a color-magnitude diagram such stars should
 - **A**: be distributed uniformly.
 - **B**: follow a single track.
 - **C**: be located in a single locus.

Main sequence

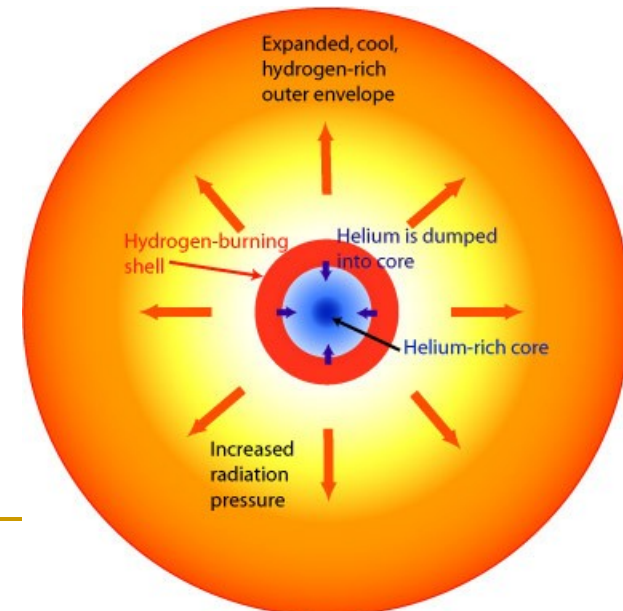
- Stars along the main sequence burn hydrogen at their cores.
- All nuclear reactions are very sensitive to the temperature: a tiny increase in temperature produces a large increase in energy output.
- The more massive a star, the stronger the gravity, the stronger must be the pressure, the hotter must be the star.
- Temperatures at the stellar cores do not vary much, but temperatures at the surfaces do.

Some Numbers

| Mass | Radius | Luminosity | Age | Temp. |
|--------------------|---------------------|----------------------------------|-----------|----------|
| 0.1 M _☉ | 0.13 R _☉ | 0.0008 L _☉ | 3,000 Gyr | 3,000 K |
| 0.5 M _☉ | 0.6 R _☉ | 0.09 L _☉ | 60 Gyr | 4,000 K |
| 1.0 M _☉ | 1.0 R _☉ | 1.0 L _☉ | 12.5 Gyr | 6,000 K |
| 10 M _☉ | 6.3 R _☉ | 3,000 L _☉ | 30 Myr | 20,000 K |
| 100 M _☉ | 30 R _☉ | 4x10 ⁶ L _☉ | 3 Myr | 50,000 K |

Beyond Main Sequence

- More massive stars are hotter, way more luminous, and live much shorter.
- When the hydrogen in the core is mostly consumed, energy production slows down, and the helium-rich core starts to compress. Compression stops when helium becomes solid (supported by ***degenerate pressure***).



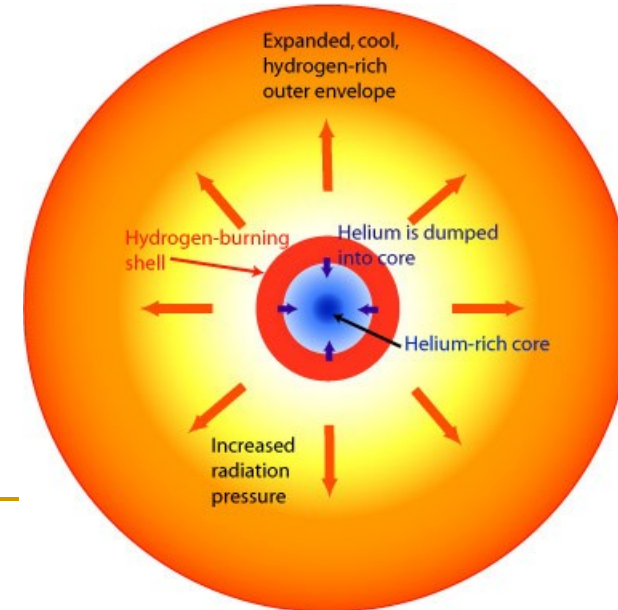
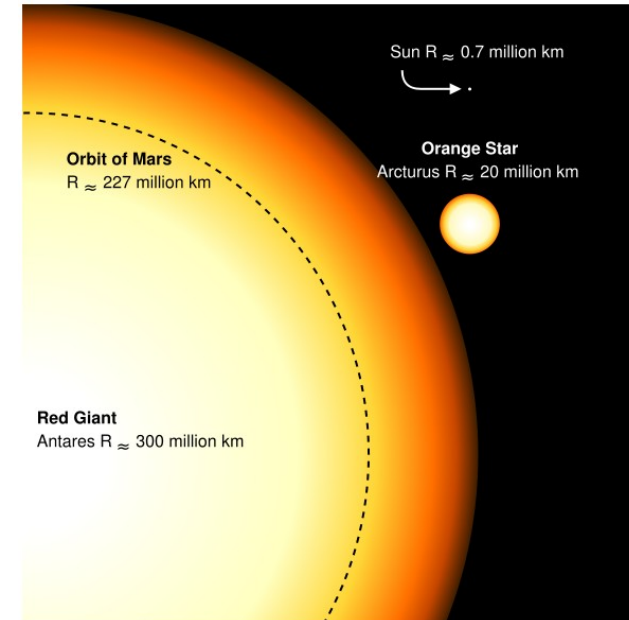
Hydrogen Shell Burning on the Red Giant Branch

Question:

- How long does it take for the Helium-rich core to compress?
 - ❑ **A:** 10 seconds
 - ❑ **B:** 1 year
 - ❑ **C:** 15,300 years
 - ❑ **D:** 20 million years
 - ❑ **E:** 1 billion year

Red Giants

- Hydrogen burns in a shell around solid helium core.
- It burns so fast, the whole star has to expand up to 100 fold (to reduce pressure); its luminosity increases up to 1,000 fold.
- Such a star is called a ***Red Giant***.



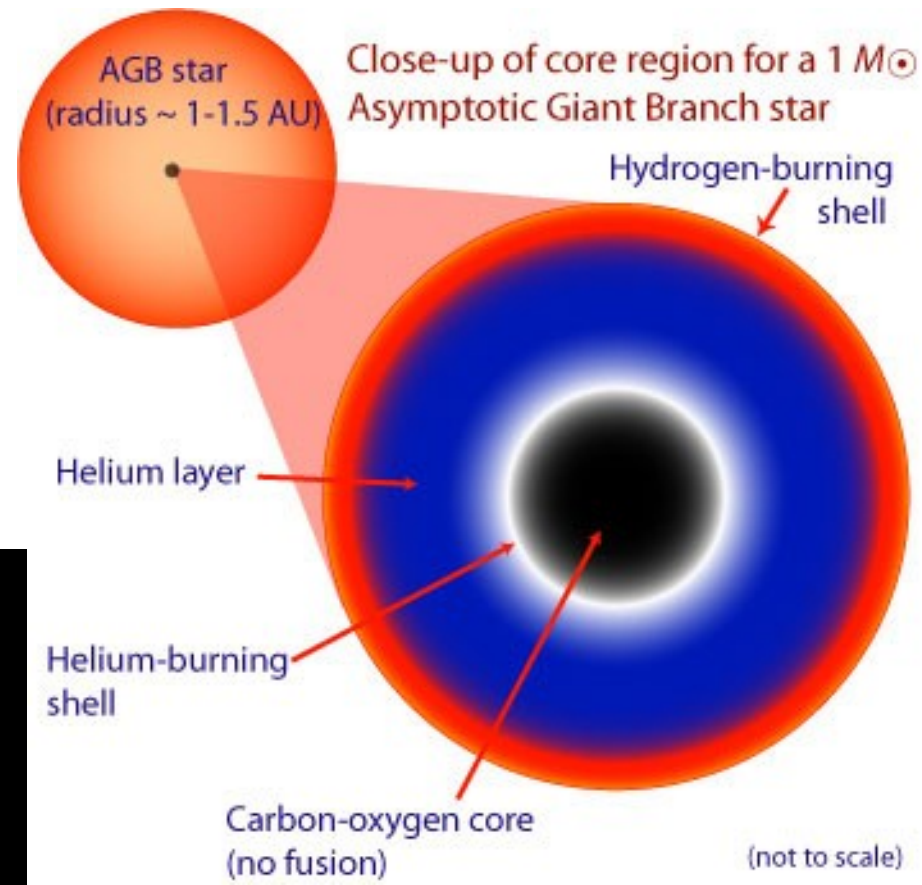
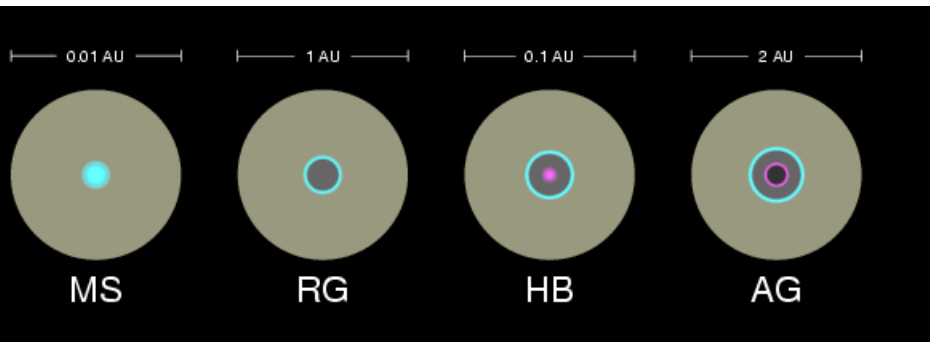
Hydrogen Shell Burning on the Red Giant Branch

Horizontal Branch

- For stars more massive than $\frac{1}{2} M_{\odot}$, the helium core eventually ignites in a ***helium flash***.
 - The core expands, and the hydrogen-burning shell cools off.
 - The star shrinks to 10 times its original size, and becomes a ***horizontal branch star***.
 - It also gets hotter at the surface, hence blue(er).
-

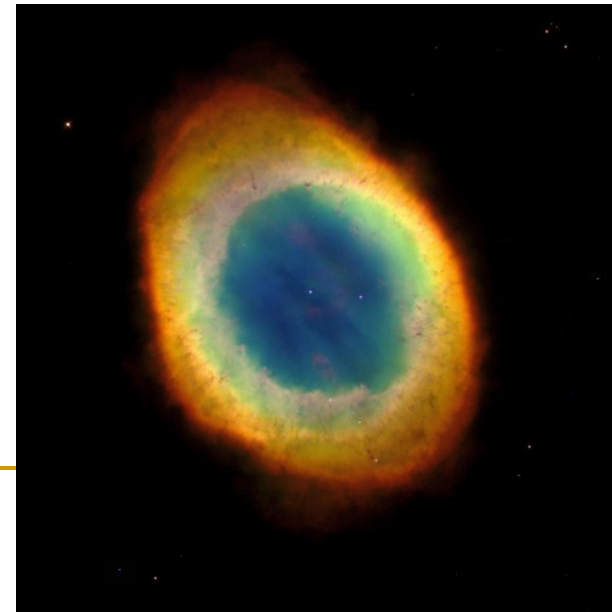
Asymptotic Giant Branch

- Eventually, helium in the core burns into carbon and oxygen, the core collapses even further, and helium ignites in a shell.
- The star becomes a red giant again, moving to the *asymptotic giant branch* (AGB).

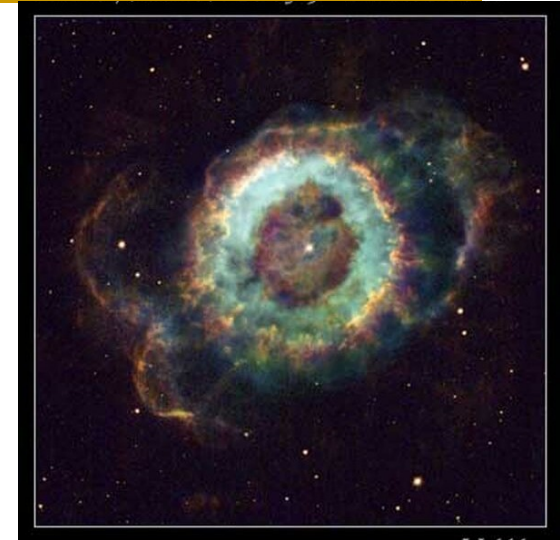


The end of the story

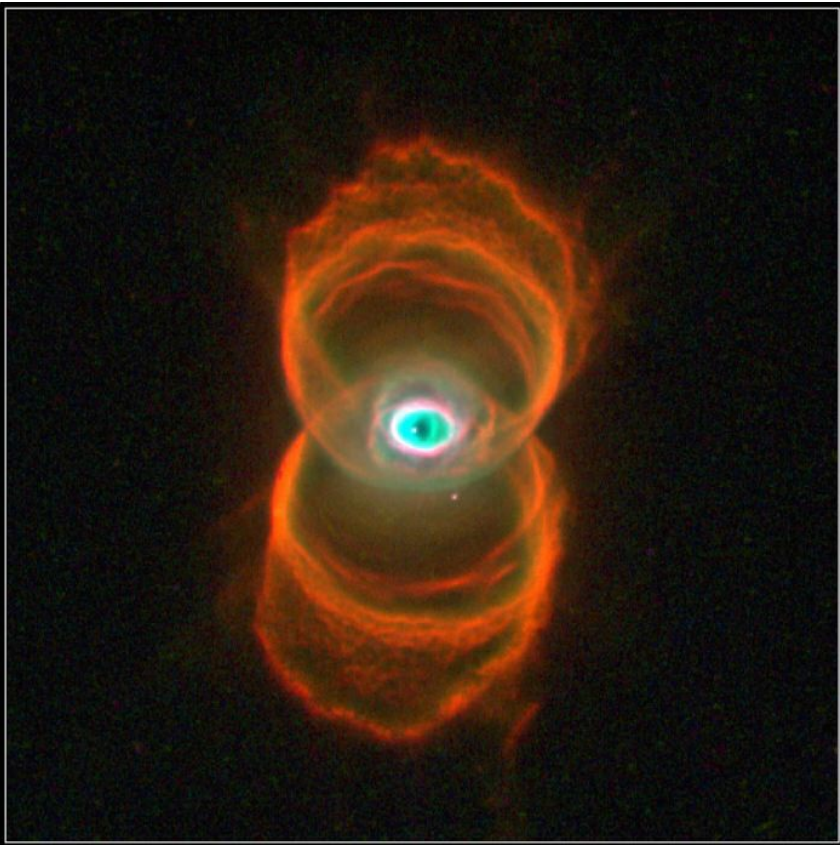
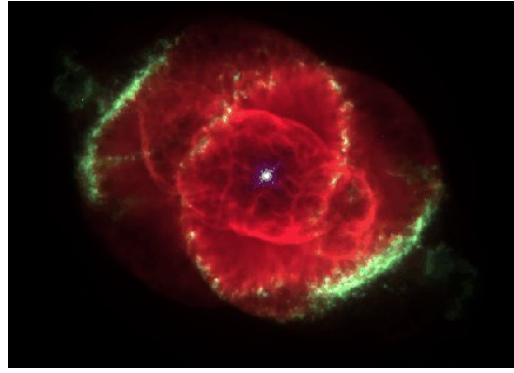
- On the AGB branch, as the carbon & oxygen core continues to compress, the star keeps getting even hotter, and keeps expanding.
- Eventually, the outer layers get fed up with all the upheavals at the core, and gracefully depart into space.
- Thus, a ***planetary nebula*** (PN) forms.
- What's left of the star is the carbon – oxygen core, called a ***white dwarf*** (WD).



Planetary nebulae



Planetary nebulae

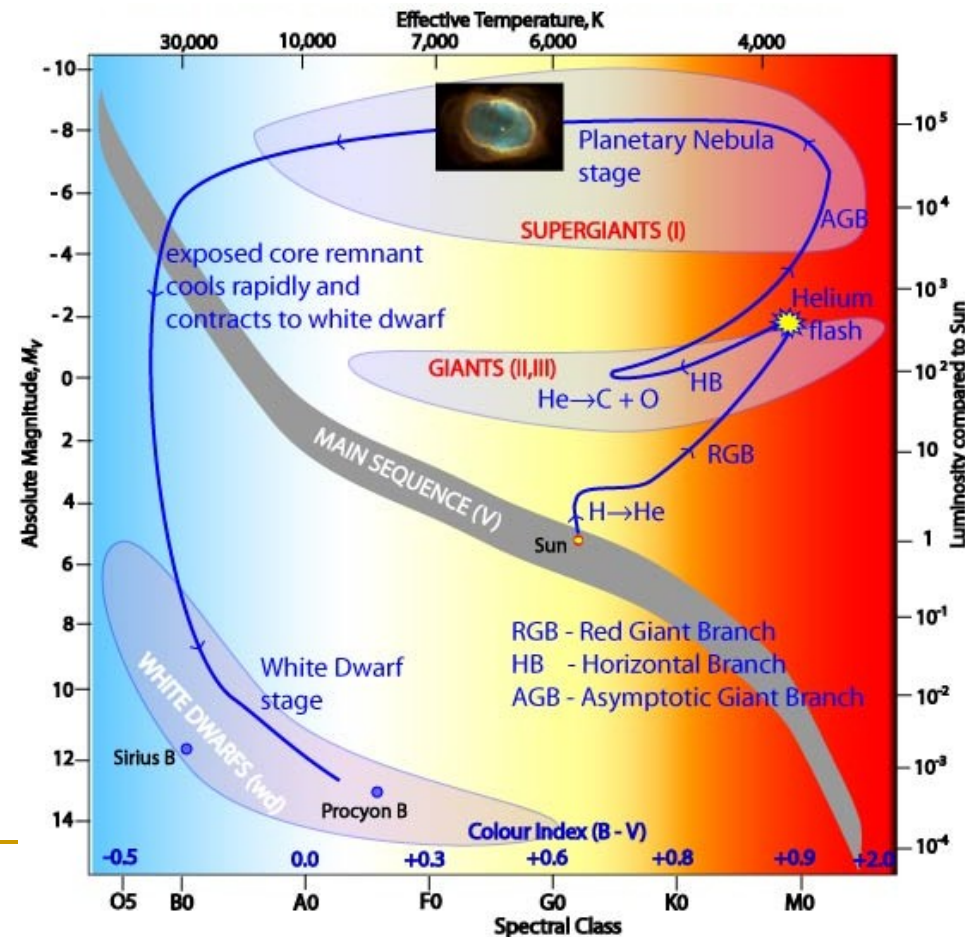


Dancing in color (and magnitude)

- On a CMD, a star follows an **evolutionary track**.

- Timeline:

- ❑ MS: 11 Gyr
- ❑ RGB: 1.3 Gyr
- ❑ HB: 160 Myr
- ❑ AGB: 5 Myr
- ❑ PN: 100,000 yr
- ❑ WD: eternity



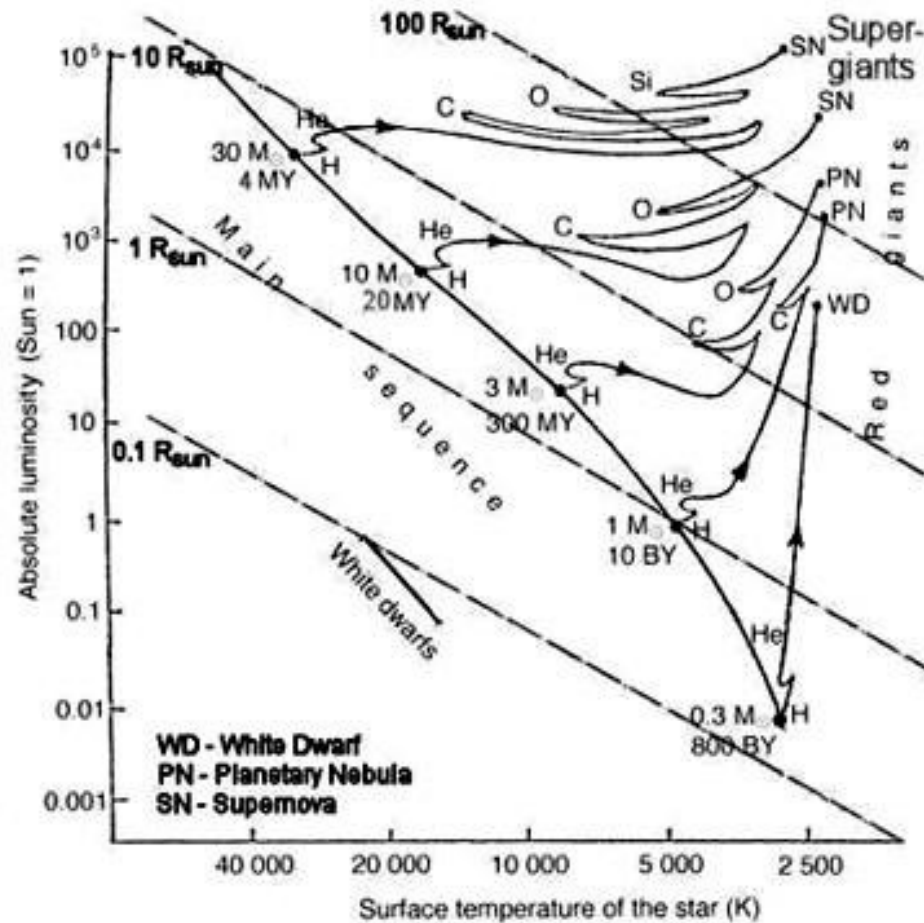
Brighter lives of massive stars

- More massive stars pass through other burning stages.

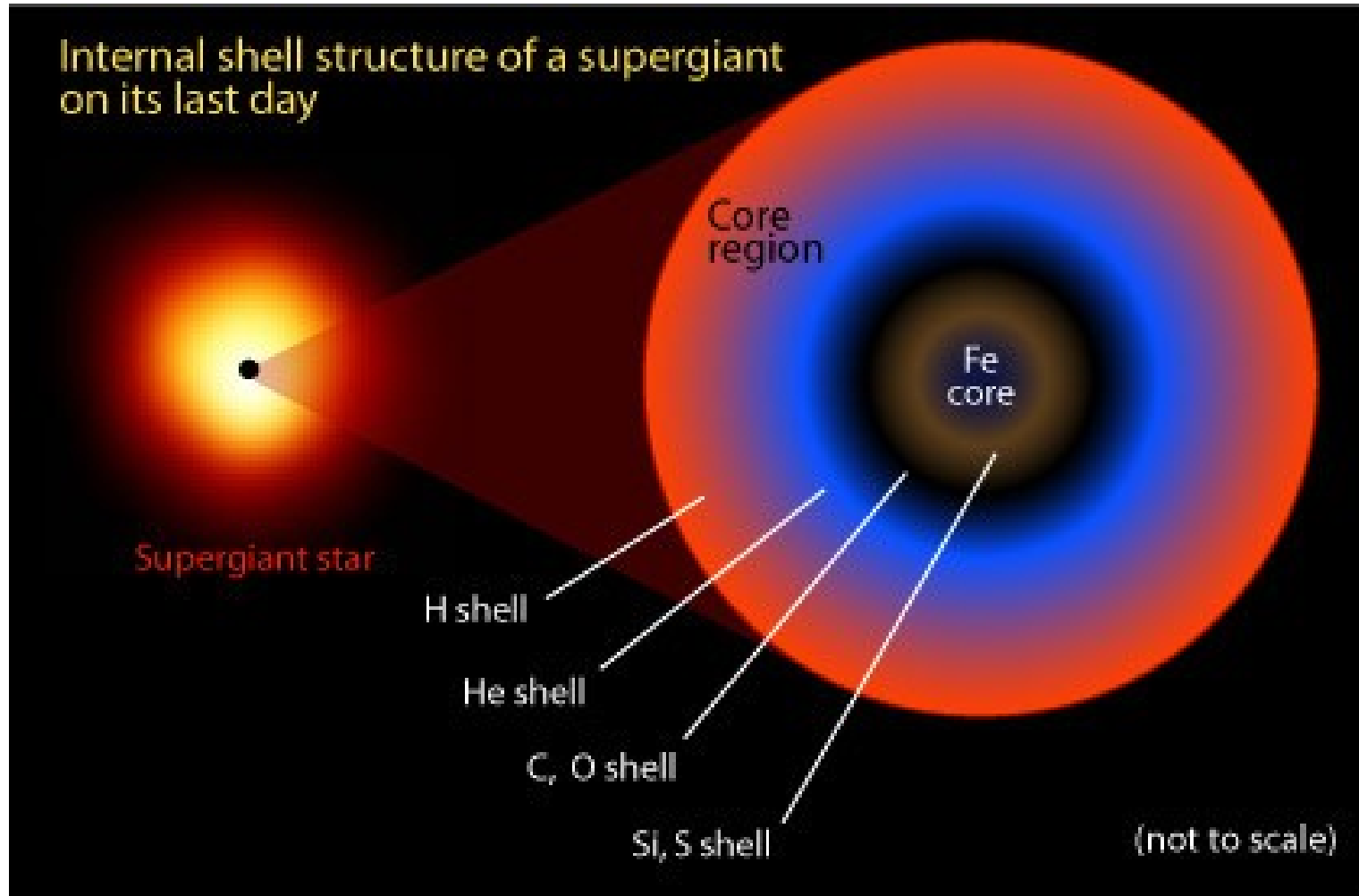
- ***They burn fast!***

A $30 M_{\odot}$ star:

- $H \Rightarrow He$: 10 Myr
- $He \Rightarrow C, O$: 1 Myr
- $C \Rightarrow Ne, Na$: 1000 yr
- $Ne \Rightarrow Na, Mg$: 3 yr
- $O \Rightarrow Si, S, P$: 100 d
- $Si, S \Rightarrow Fe$: 3 d



Star's last day



... and what happens tomorrow we will learn next time...